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MEMORANDUM FOR PRS (In-HousePublication)

FROM: PROI (TI) (STINFO) 10 September 1999

SUBJECT: Authorization for Release of Technical Information, Control Number: AFRL-PR-ED-TP-FY99-0180, Karen Olson, "Material Property Sensitivities on Cryo Upperstage Rocket Engines," **26th Annual Western Regional Conference** **(Statement A)**

Material Property Sensitivities on Cryo Upperstage Rocket Engines

Karen Olson
Applications and Assessments Branch
Propulsion Sciences & Advanced Concepts Division
AFRL/PRST

Overview

- Objective
- Baseline & Demonstrator Engine Description
- Material / Engineering Limits
- Sensitivities
- Weight Estimations
- Impact on Payload
- Conclusion
- Recommendation

Study Objective

Identify the critical material properties that enable a demonstrator engine to meet **I**ntegrated **H**igh **P**ayoff **R**ocket **P**ropulsion **T**echnology (IHPRPT) performance (Isp and thrust-to-weight) goals.

IHPRPT Goals

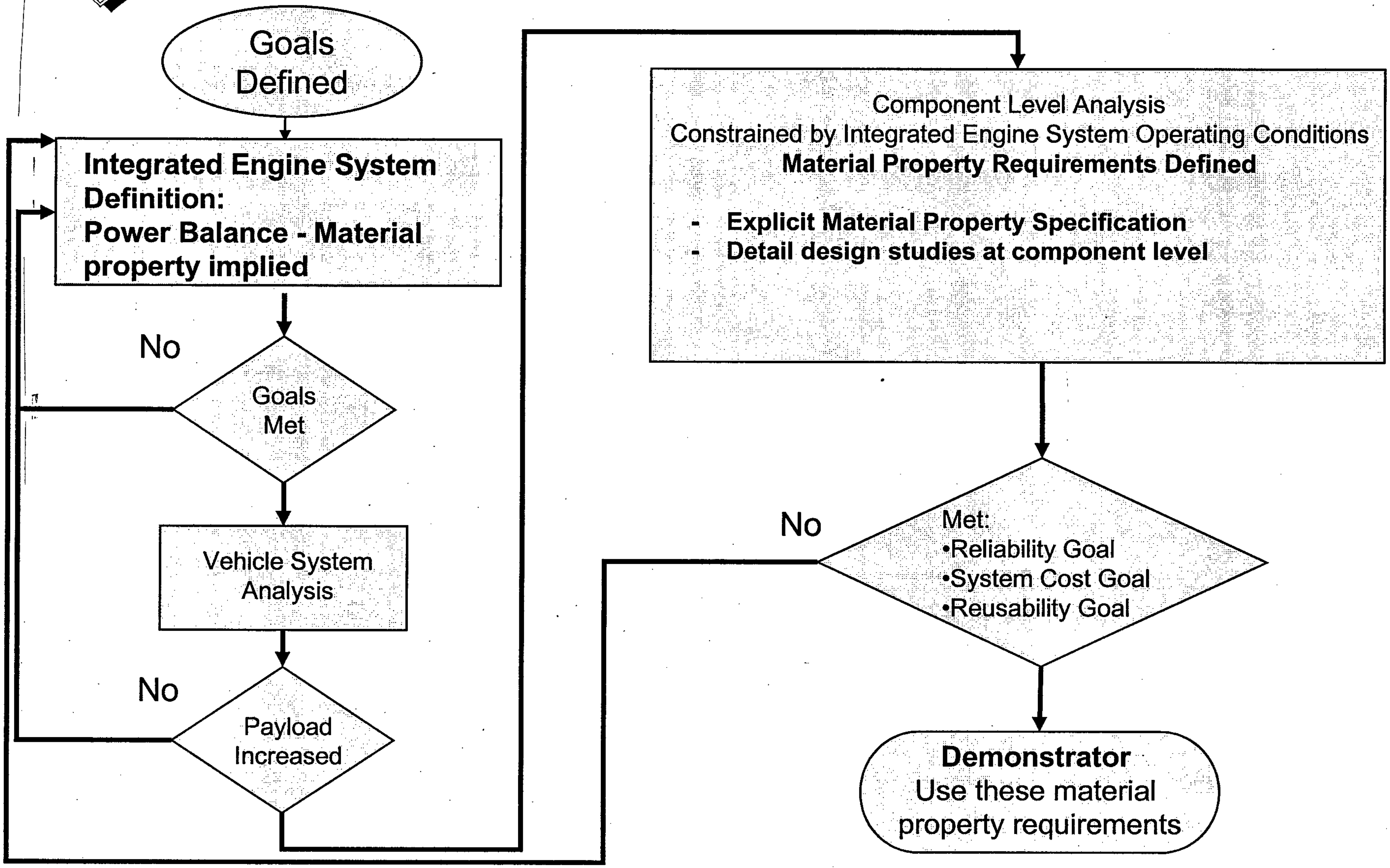
Boost and Orbit Transfer Propulsion	2000	2005	2010
• Reduce Stage Failure Rate	25%	50%	75%
• Improve Mass Fraction (Solids)	15%	25%	35%
• Improve I~~SP~~ (sec)	14	21	26
• Reduce Hardware Costs	15%	25%	35%
• Reduce Support Costs	15%	25%	35%
• Improve Thrust to Weight (Liquids)	30%	60%	100%
• Mean Time Between Removal (Mission Life-Reusable)	20	40	100

lower case to match second group

Spacecraft Propulsion			
• Improve I_{tot}/Mass $_{(wet)}$ (Electrostatic/Electromagnetic)	20%/200%	35%/500%	75%/1250%
• Improve Isp (Bipropellant/Solar Thermal)	5%/10%	10%/15%	20%/20%
• Improve Density-Isp (Monopropellant)	30%	50%	70%
• Improve Mass Fraction (Solar Thermal)	15%	25%	35%

Tactical Propulsion			
• Improve Delivered Energy	3%	7%	15%
• Improve Mass Fraction (Without TVC/Throttling)	2%	5%	10%
• Improve Mass Fraction (With TVC/Throttling)	10%	20%	30%

Liquid Rocket Engine Material Property Requirement Generation Flow Diagram



Performance Goals for Cryogenic Upperstage Rocket Engine

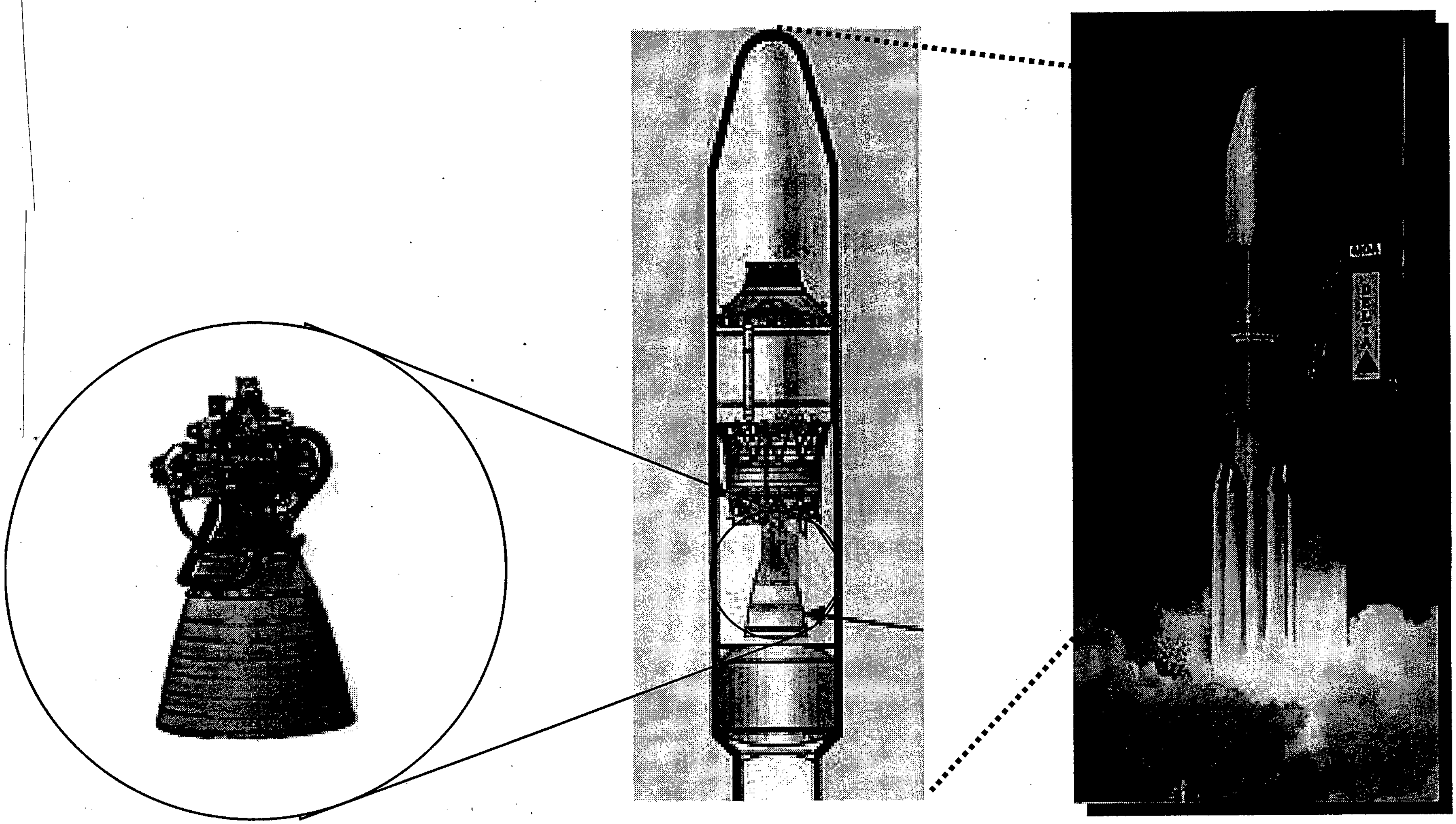
Goals:

- Isp improvement of 3% over Baseline
- Thrust-to-weight improvement of 100% better than Baseline

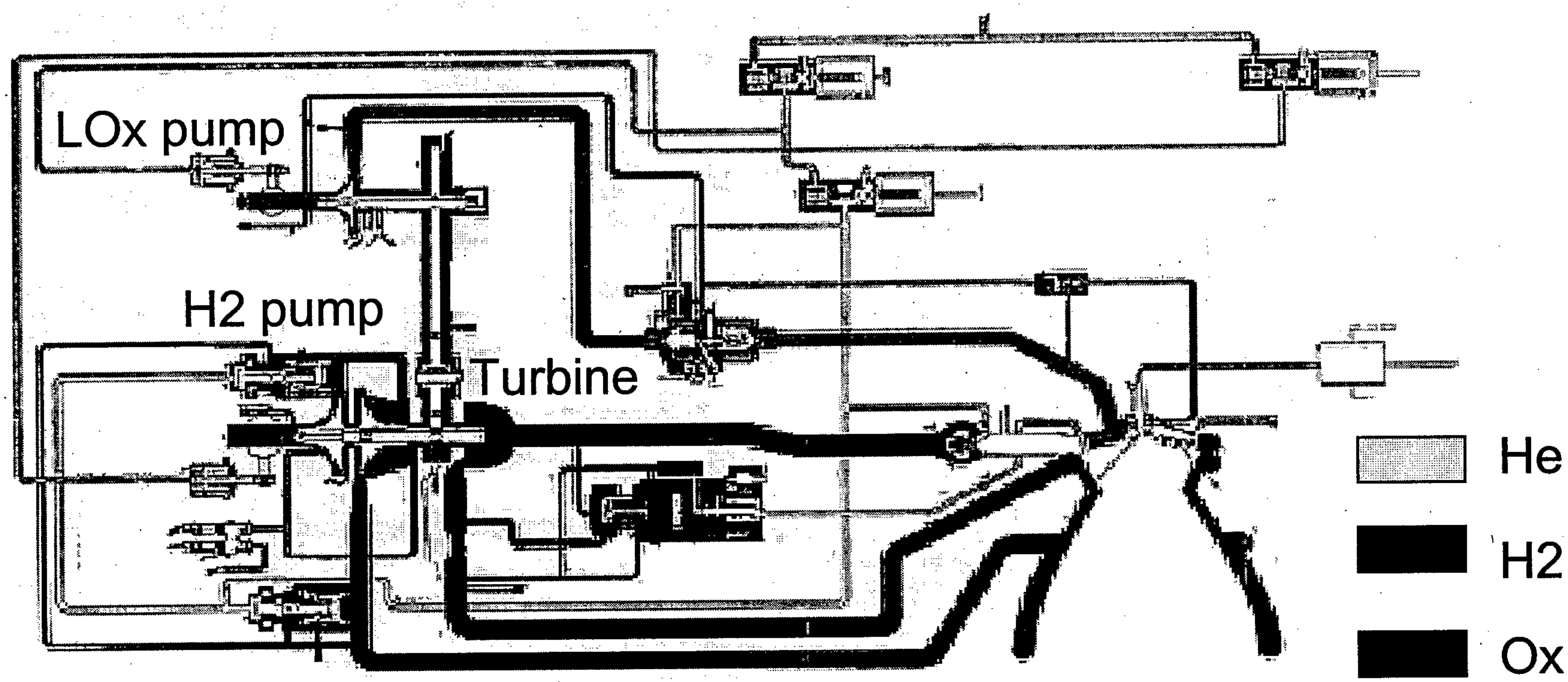
Baseline & Demonstrator Engine Comparison

	Baseline Engine	Demonstrator - Space
Thrust	16,500 lbs	50,000lbs
Mixture Ratio	5.0	5.0
Chamber Pressure	500 psia	2000 psia
Nozzle Area Ratio	60:1	170:1
Turbopump Description	2-stage Fuel	3-stage Fuel

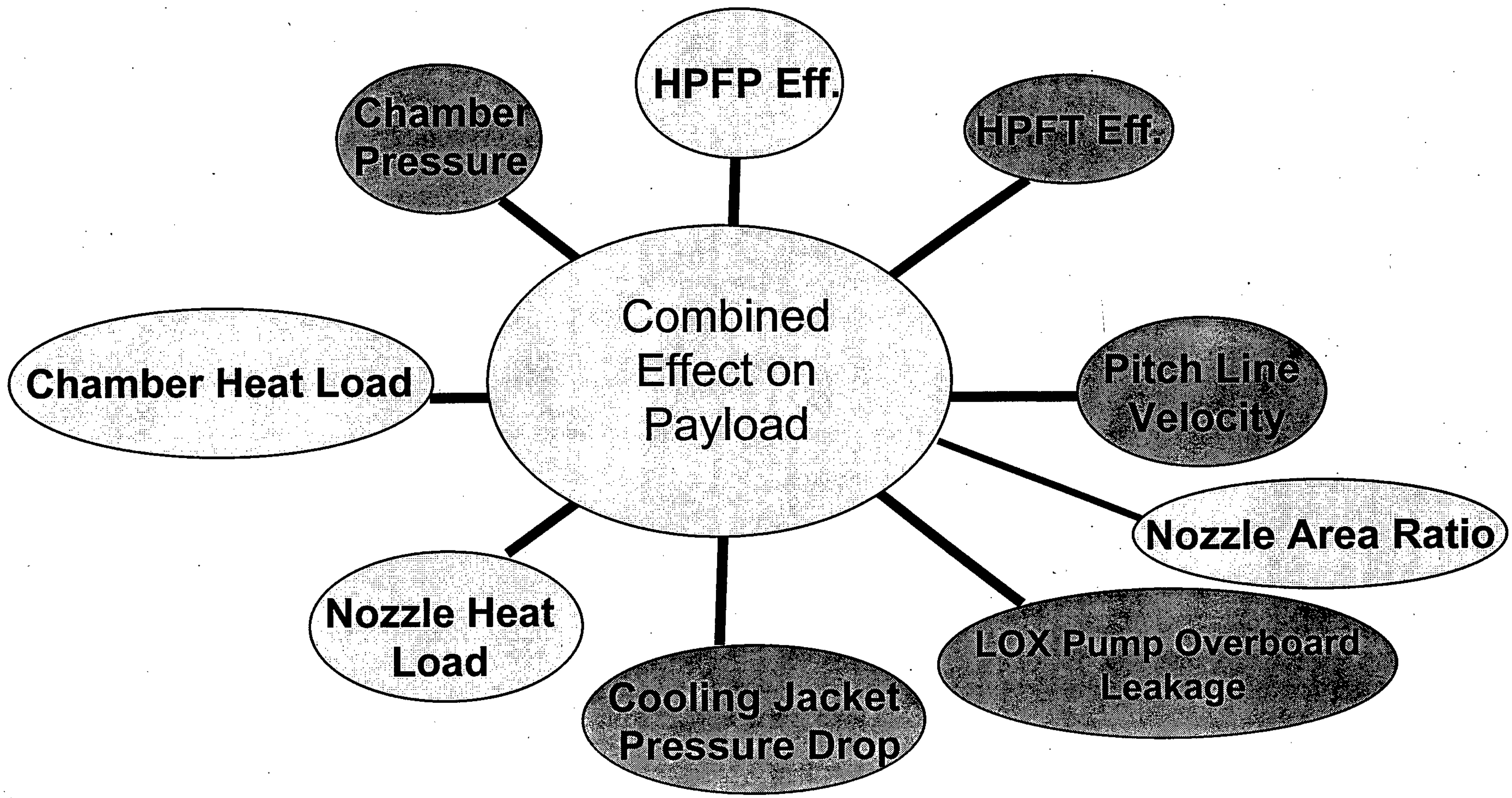
Delta III Configuration



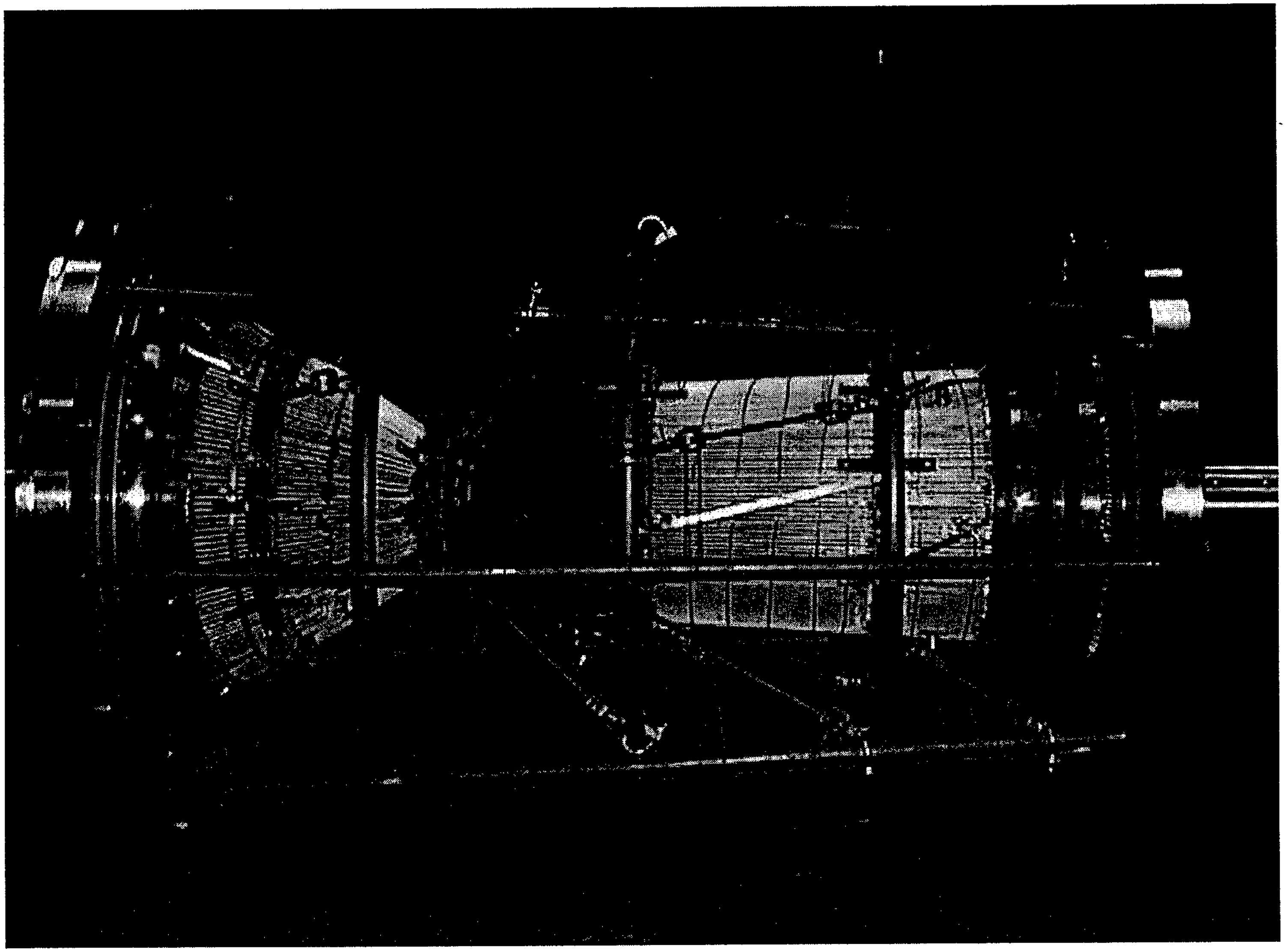
Baseline Flow Schematic



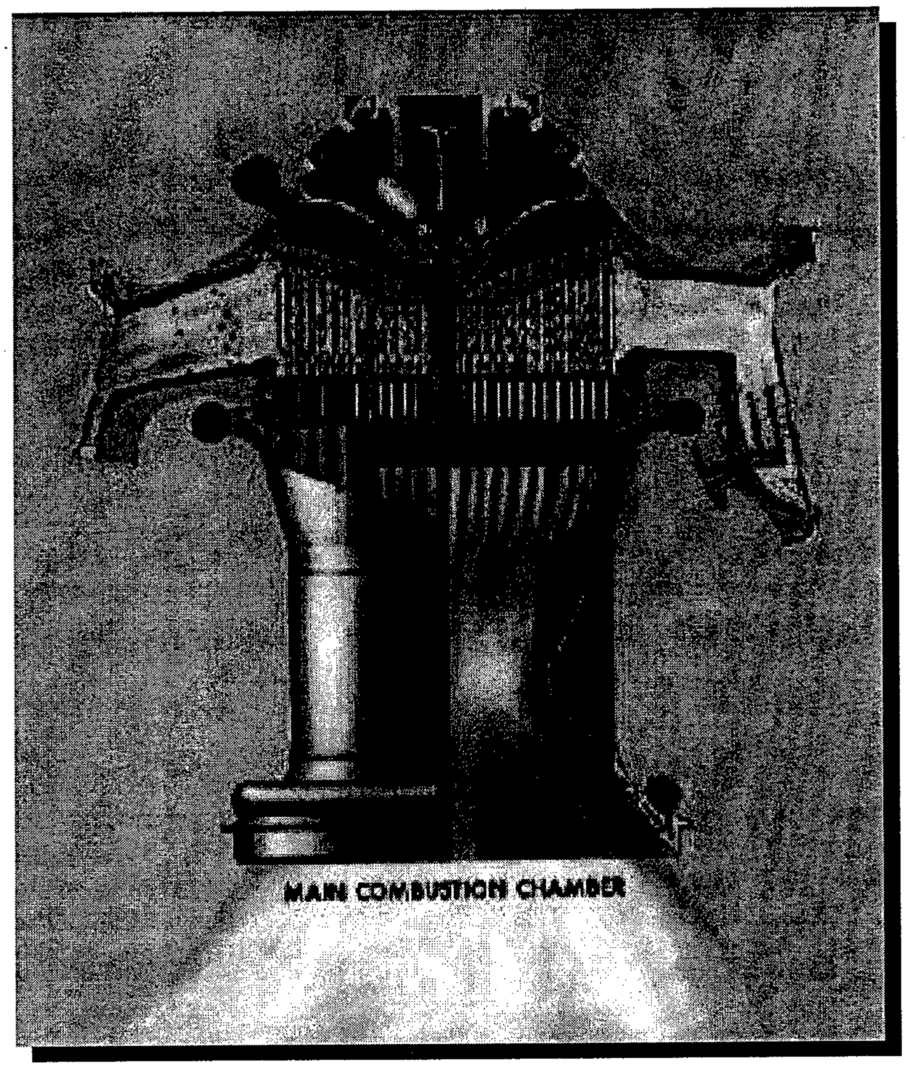
Engine Modifications



Advanced Expander Combustor



Powerhead–Showing Chamber Detail

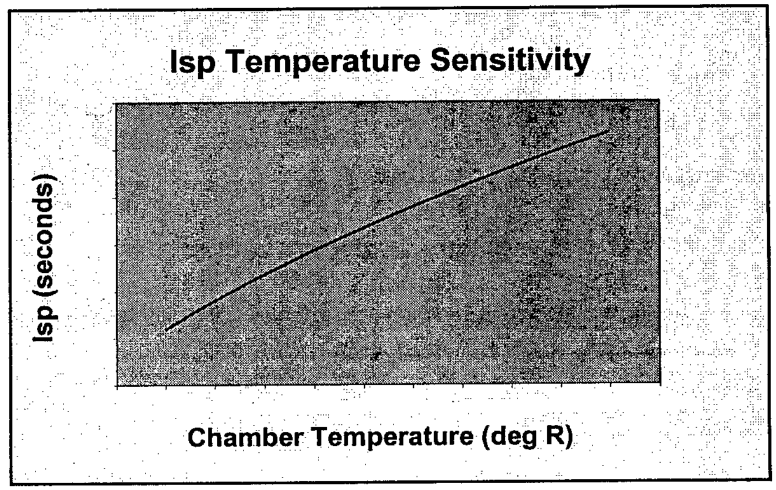


Material Limits Impacting Performance
Combustion Chamber

Main combustion chamber wall temperature limit about 1100° F with Ox/H2 propellants

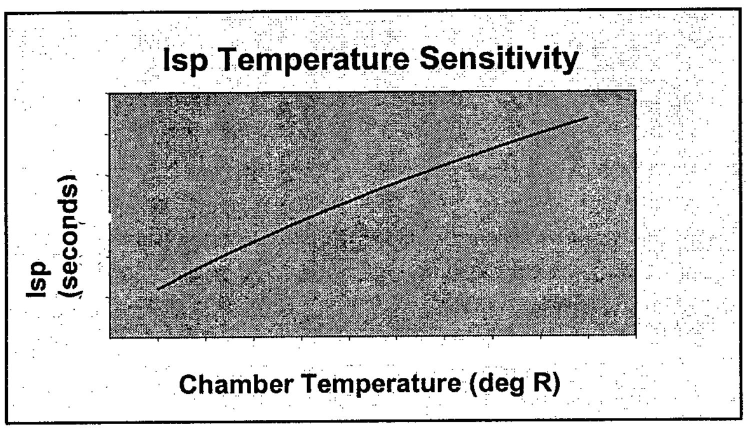
– Performance penalties :
  - Film cooling requirement for low grain growth temperature - Isp loss from unreacted propellant
  - Lowered heat load transferred to coolant due to high resistance in material (thermal conductivity, low yield strength) and design - Turbopump reliability loss from increased pressure requirement

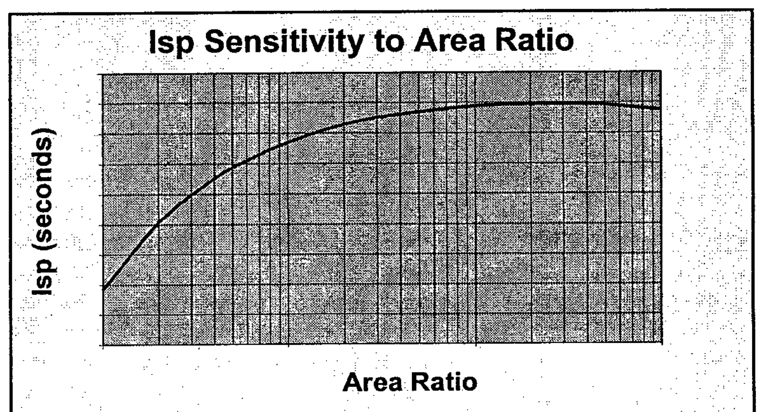
	Stainless Steel	Narloy-Z
Thermal Conductivity (W/M-K)	22	350
Yield Strength (inches)	72,413	13,000



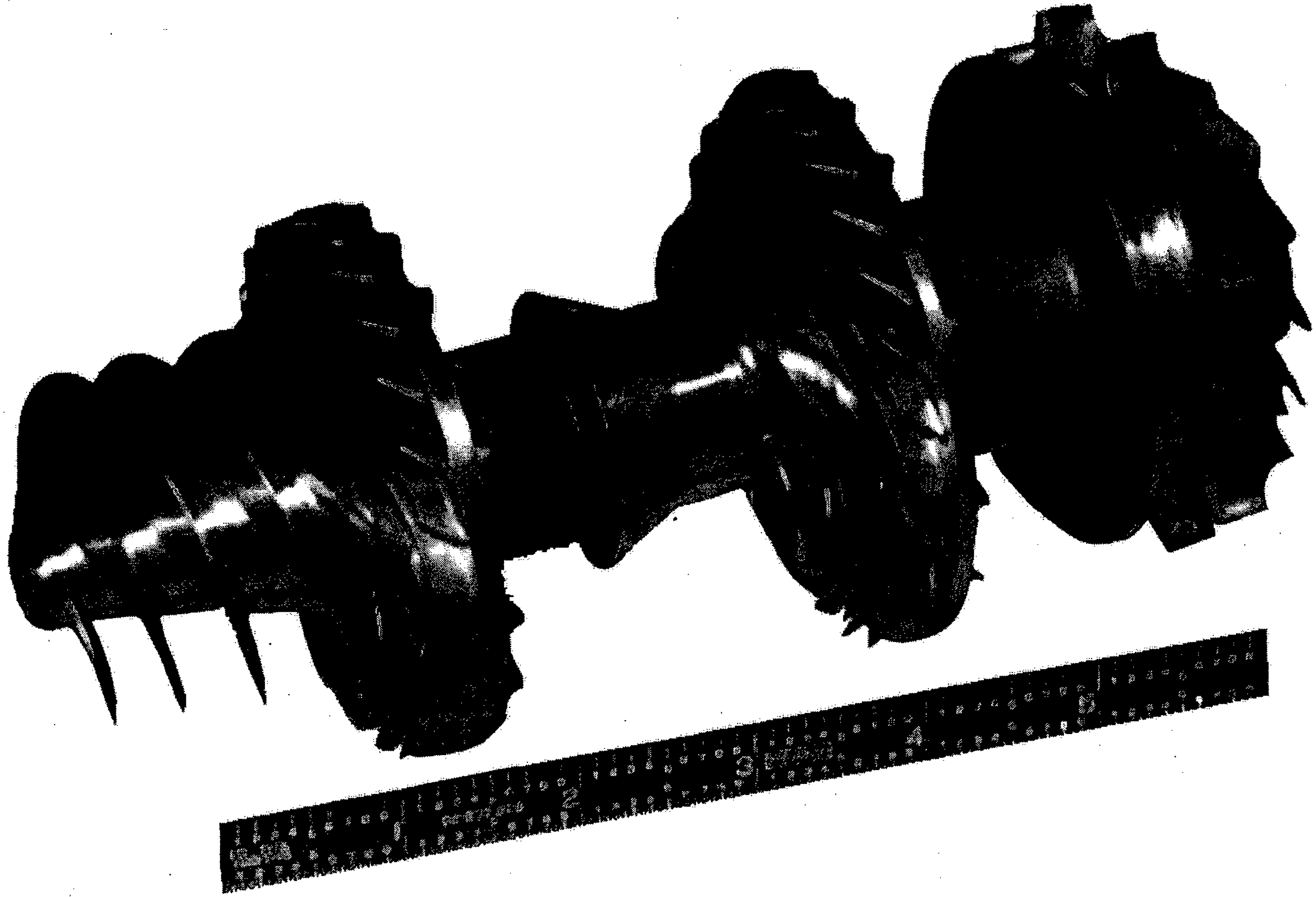
Material Limits Impacting Performance Nozzle

- Weight gain
  - Requires reduction in nozzle area ratio
  - Lead to decreased Isp and thrust
- Temperature limitation
  - Reduces power available to the turbine
  - Leads to decreased thrust and/or reliability (depending on how the pressure loss is divided)
- Current material: 347 Stainless Steel
  - Specific Strength (Yield Strength / Density) = 93,103 in

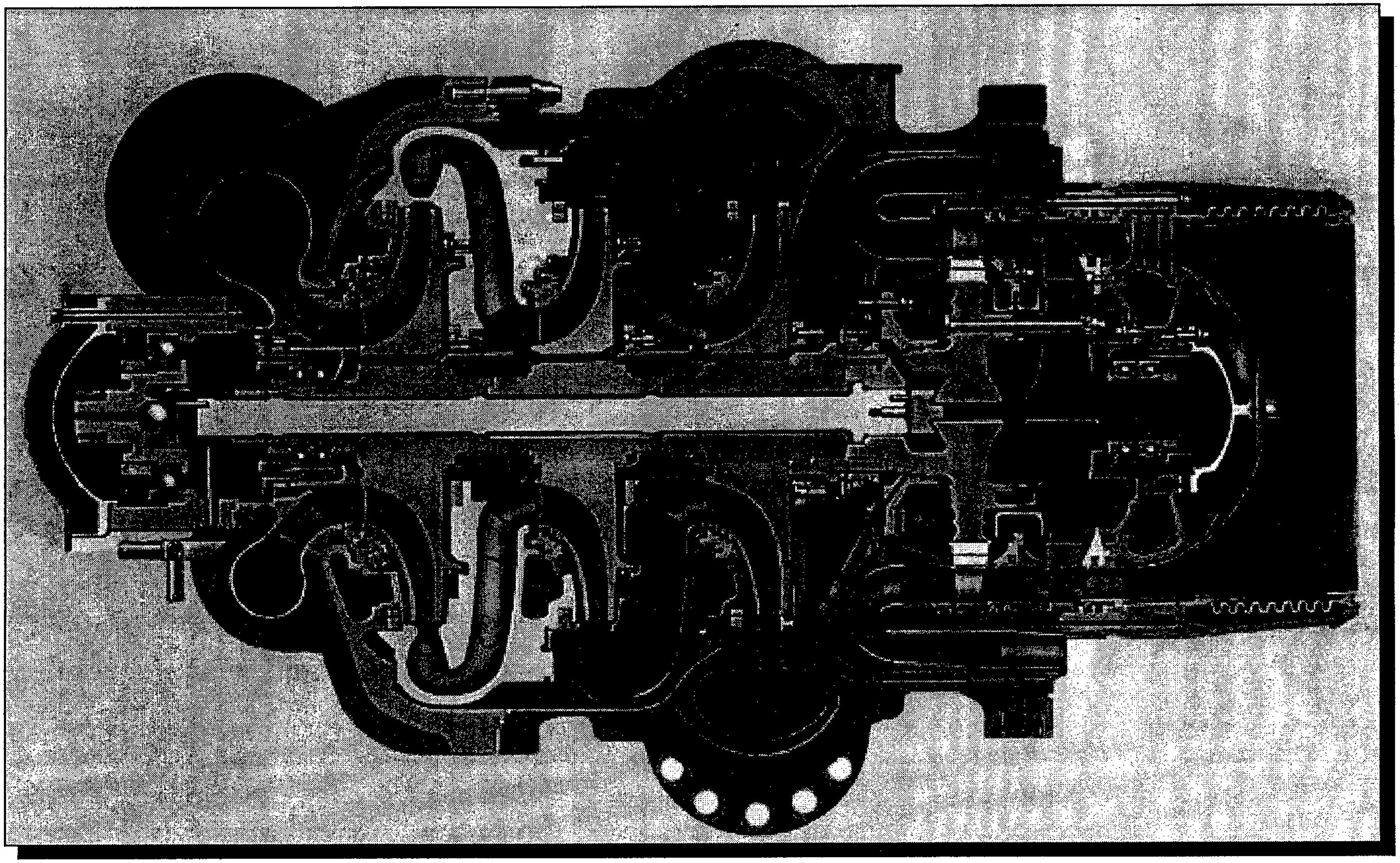




Advanced Liquid Hydrogen Turbopump



Turbopump

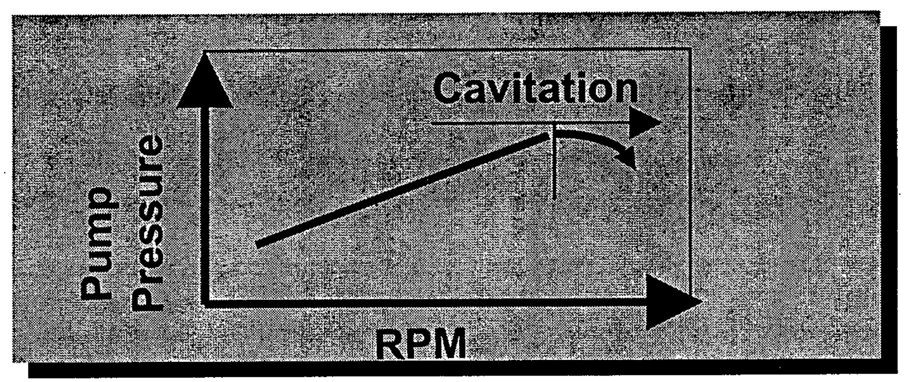


Material Limits Impacting Performance
Turbopump

Turbopump shaft speed limits:

- Turbine AN^2 - tensile strength and creep at high temp
- Bearing DN - modulus of elasticity & rigidity
- Pump impeller tip speeds - same as turbine
- why bold? **Pump labyrinth seal clearance** - heat distortion temp

Lower shaft speed = Less available pressure to produce thrust



Existing Labyrinth Seal material: Kel - F
Heat Distortion Temp: 259 deg F

Material and Engineering Limits Exploited

to what do the asterisks refer?

Table II Engineering (Material) Limits Varied for Sensitivity

	Representative Material Property	**Normal Limit**	**Increased Limit**
Turbopump			
Pump Eff.	**Heat Distortion Temp & Internal Friction of the Seal Material**	**10% Drop in Efficiency 259 °F***	**0% Drop in Efficiency Property Requires Research**
Impeller Tip Speed	Modulus-Elasticity/Rigidity	1900 ft/sec	Not Challenged, No Change Required
Turbine Eff.	Blade Melting Temp	Turbine Temperature Limit to Efficiency = 6% Loss	Turb Temp 1.5x Limit to Eff = 5% Loss Not Needed
Bearing DN	Design	20×10^6 mm x RPM	Not Challenged, No Change Required
Turbine AN2	Modulus-Elasticity/Rigidity	8 in x RPM^2	Not Challenged, No Change Required
Heat Load	**Thermal Properties of the Combustion Chamber & Nozzle**	**25,000 BTU/sec k=202.3 BTU/ft-hr-°F Melt. Temp: 2500 - 2600 °F**	**39,000 BTU/sec New Property**
Nozzle Area Ratio	**Specific Strength of Nozzle**	**175:1** Spec. Str. 74K in*****	**300:1**

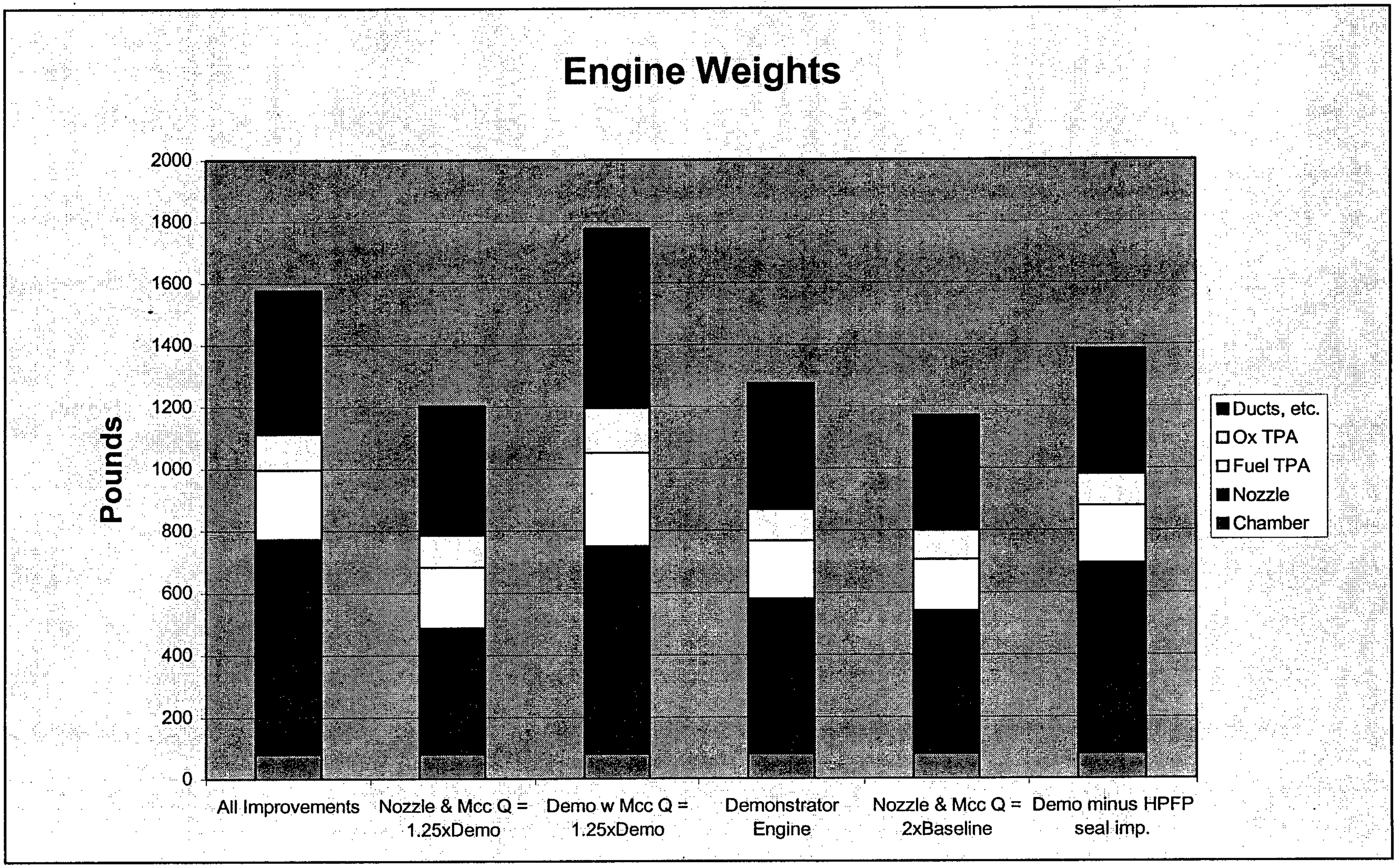
Weight Estimation Methodology (All Weights Assumed Stainless Steel)

By IMWG Direction:

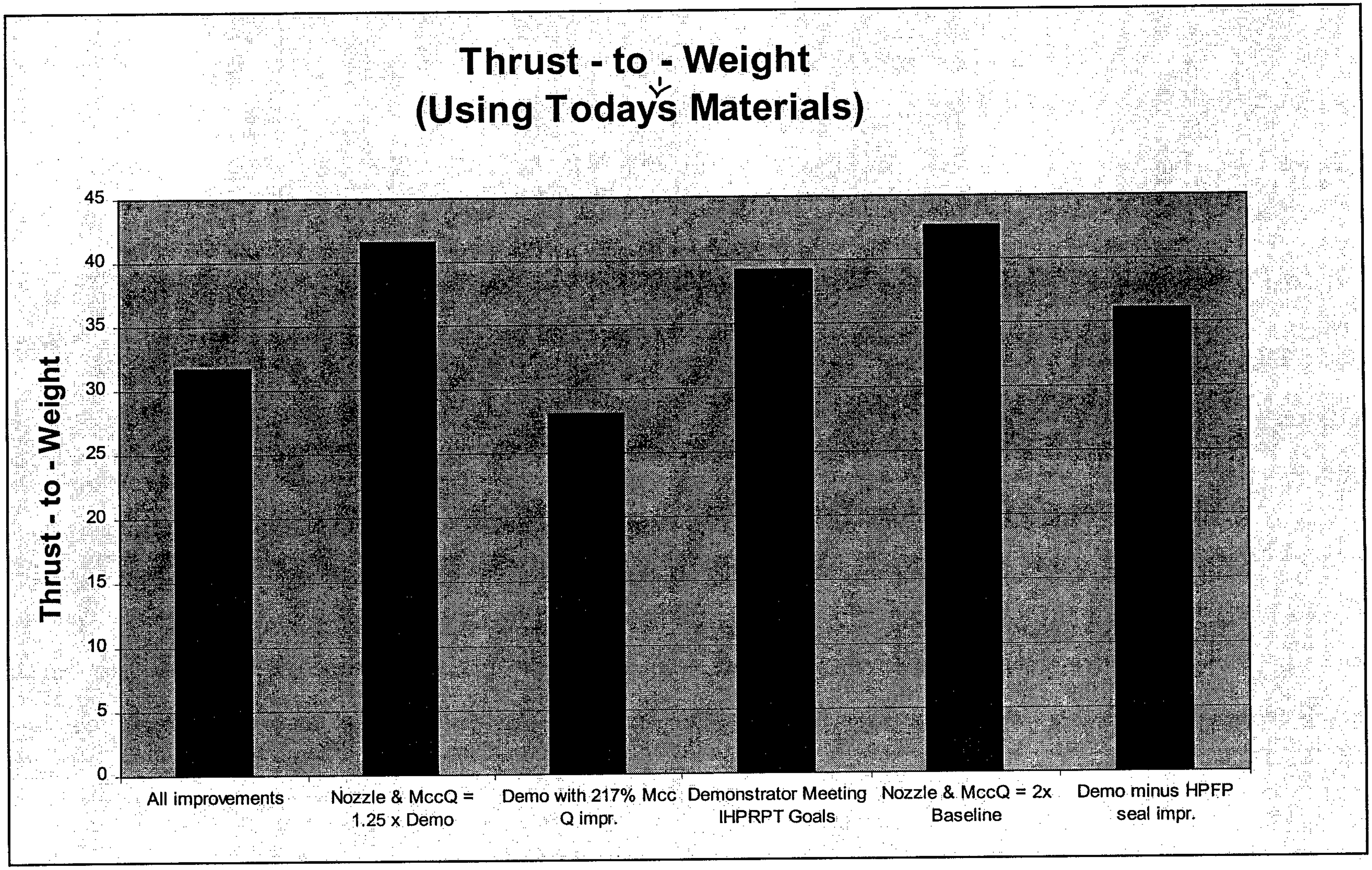
Material Property Advances are Assumed; Particular Advanced Materials are to be Selected Later

- Turbopumps & Combustion Chamber:
  - Hoop Stress Calculation - High Pressure Devices
- Nozzle
  - Method of Characteristics - For Shape and Area
    - High Pressure Across Nozzle Wall for thickness
- Remaining Hardware
  - Scaled to Turbopump and Nozzle

Engine Weight Comparison



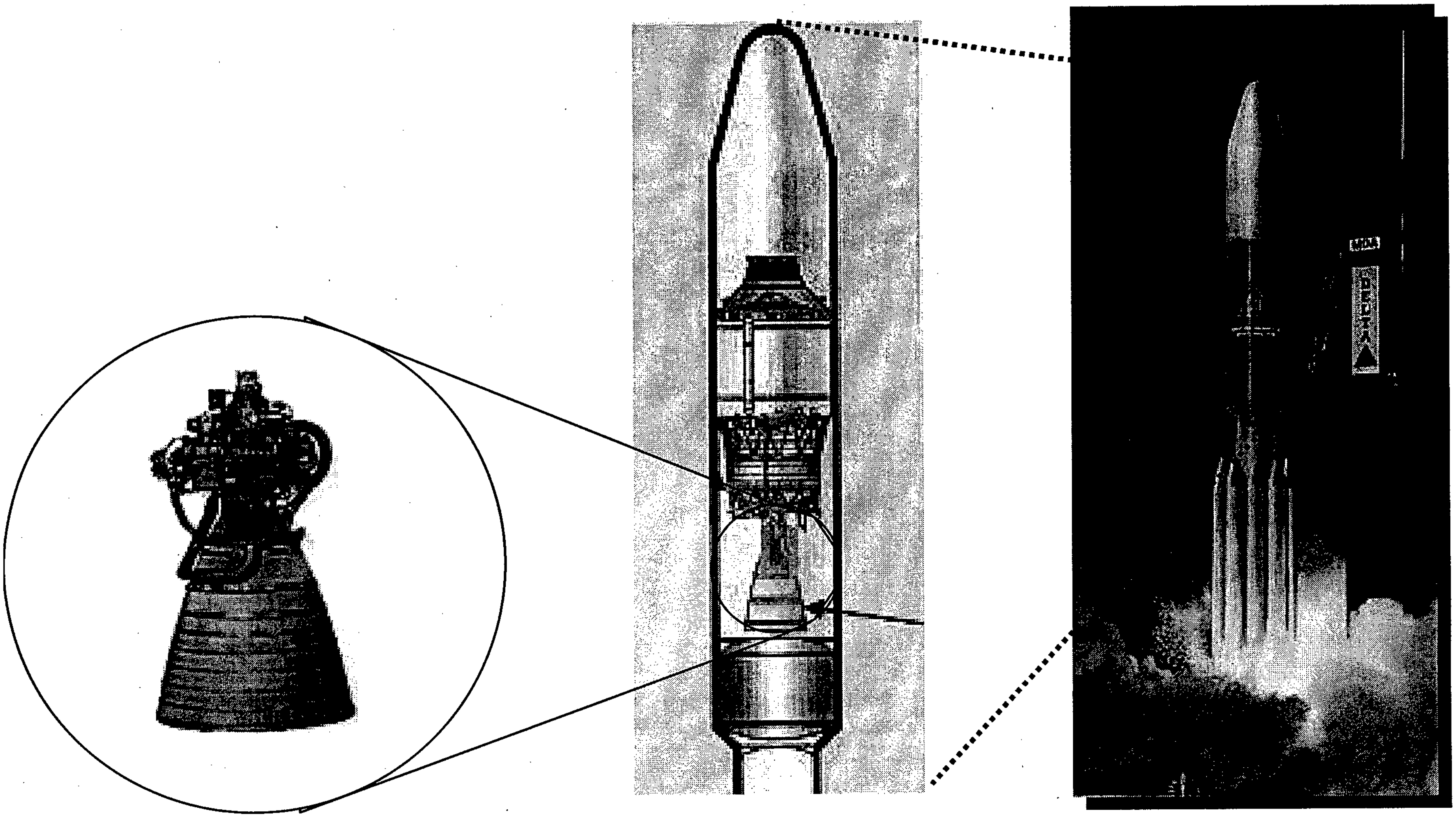
Thrust-to-Weight Comparison



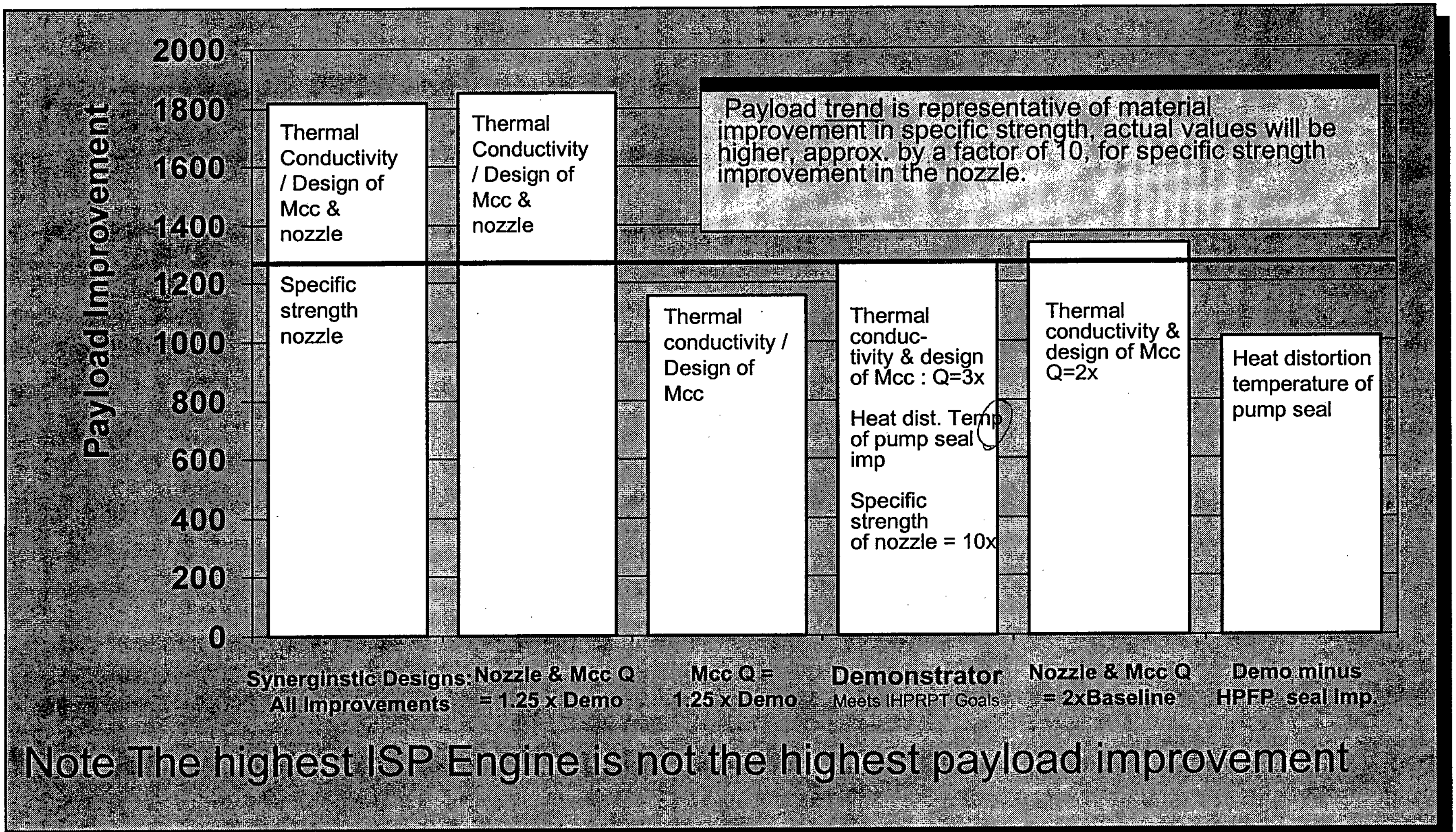
Weight Effects on Vehicle Performance

- Payload gains from the higher ISP Engines are offset by weight penalties.
- Single heaviest engine component: Nozzle - about 40% of Engine total weight
- 10x Specific Strength improvement of nozzle will result in more reasonable weight reduction in remaining components

Delta III Configuration



Resultant Delta III System Payoff to GTO



Conclusion

- Major Improvers:
  - Thermal Properties of combustion chamber and nozzle
  - Strength - to - Weight of nozzle
- Important Improver:
  - Heat Distortion Temp of Labyrinth Seal

Recommendations

- Develop material properties improving:
  - Thermal properties - grain growth temp for higher temp operation & thermal conductivity for high hoop stress in both the chamber and nozzle
  - Specific strength of material used in the nozzle
  - Heat distortion temperature in the fuel pump labyrinth seal
- Next Steps:
  - Start quantification of candidate material critical properties for this demonstrator.
    - Applied, Existing or New
  - Investigate other Engines and Applications.

AIR FORCE RESEARCH LABORATORY

Backup Charts

Some of these backups will not show up well if you have to use them — too busy.

Engine Weights

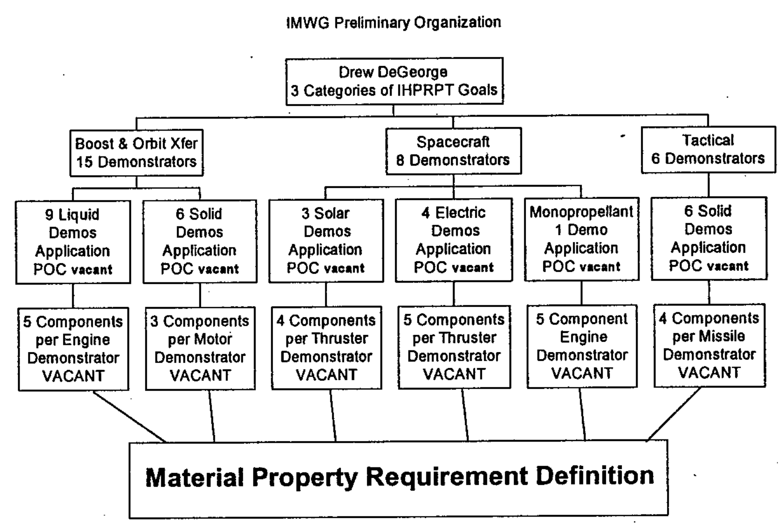
	Area Ratio	Nozzle Weight	Chamber Weight	Fuel Turbopump Weight	Lox Turbopump Weight	Ducts, Lines, & Other	Total Engine Weight
All improvements	300	692	80	224	116	464	1576
Nozzle & MccQ = 1.25 x Demo	200	407	80	194	104	418	1203
Demo with 217% Mcc Q impr.	177	669	80	301	145	582	1777
Demonstrator Meeting IHPRPT Goals	**171**	**499**	**80**	**186**	**102**	**407**	**1275**
Nozzle & MccQ = 2x RL10	170	461	80	164	93	373	1171
Demo minus HPFP seal impr.	171	612	81	185	101	406	1385

Gaps to Fill **BEFORE** Tying Material Research to IHPRPT

Step I: **Completed**
Goal definition

Step II: **Way Behind**
Rocket Design meeting goals

Step III: **Way Way Behind**
Material Property Identification



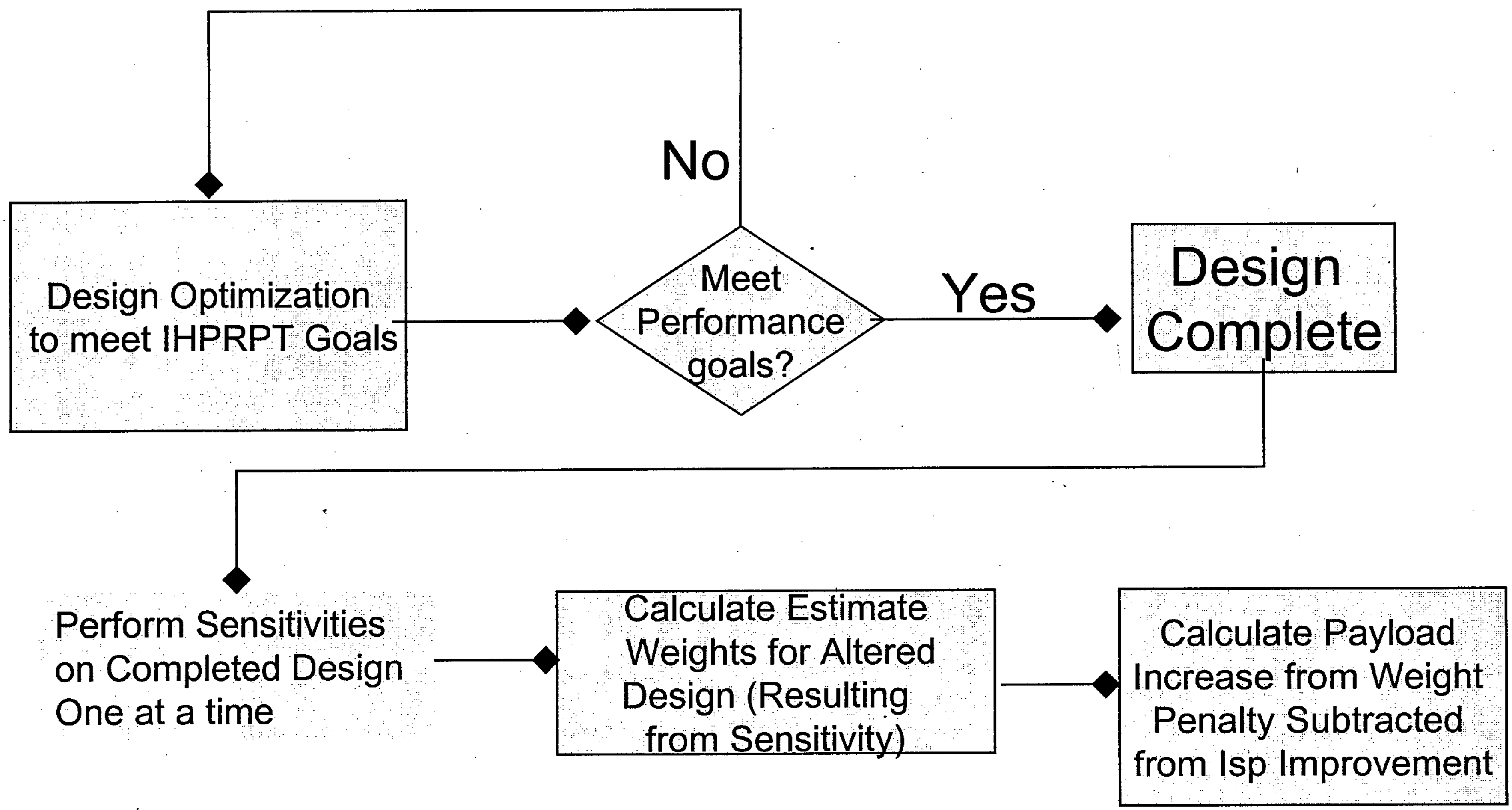
Step IV: **Completed**
Material Development Programs underway (without IHPRPT target values for their properties)

Existing Material Programs
without property values to target their results

Phase III IHPRPT Performance Goals for Cryogenic Upperstage

- Isp improvement of 3% over baseline engine
- Thrust-to-weight improvement of 100% over baseline engine

Progression from Demonstrator Optimization to Sensitivity

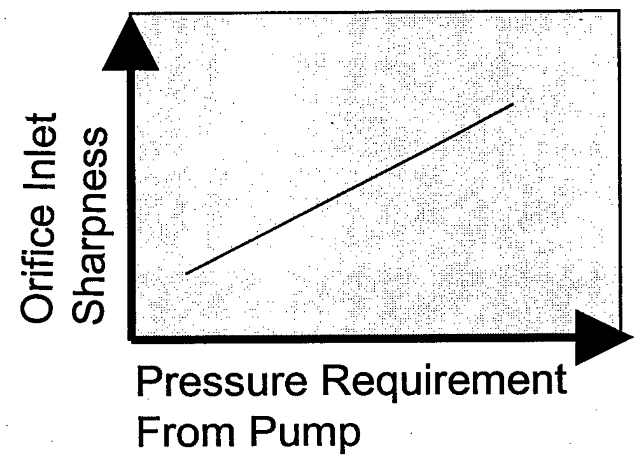


Material and Engineering Limits Exploited

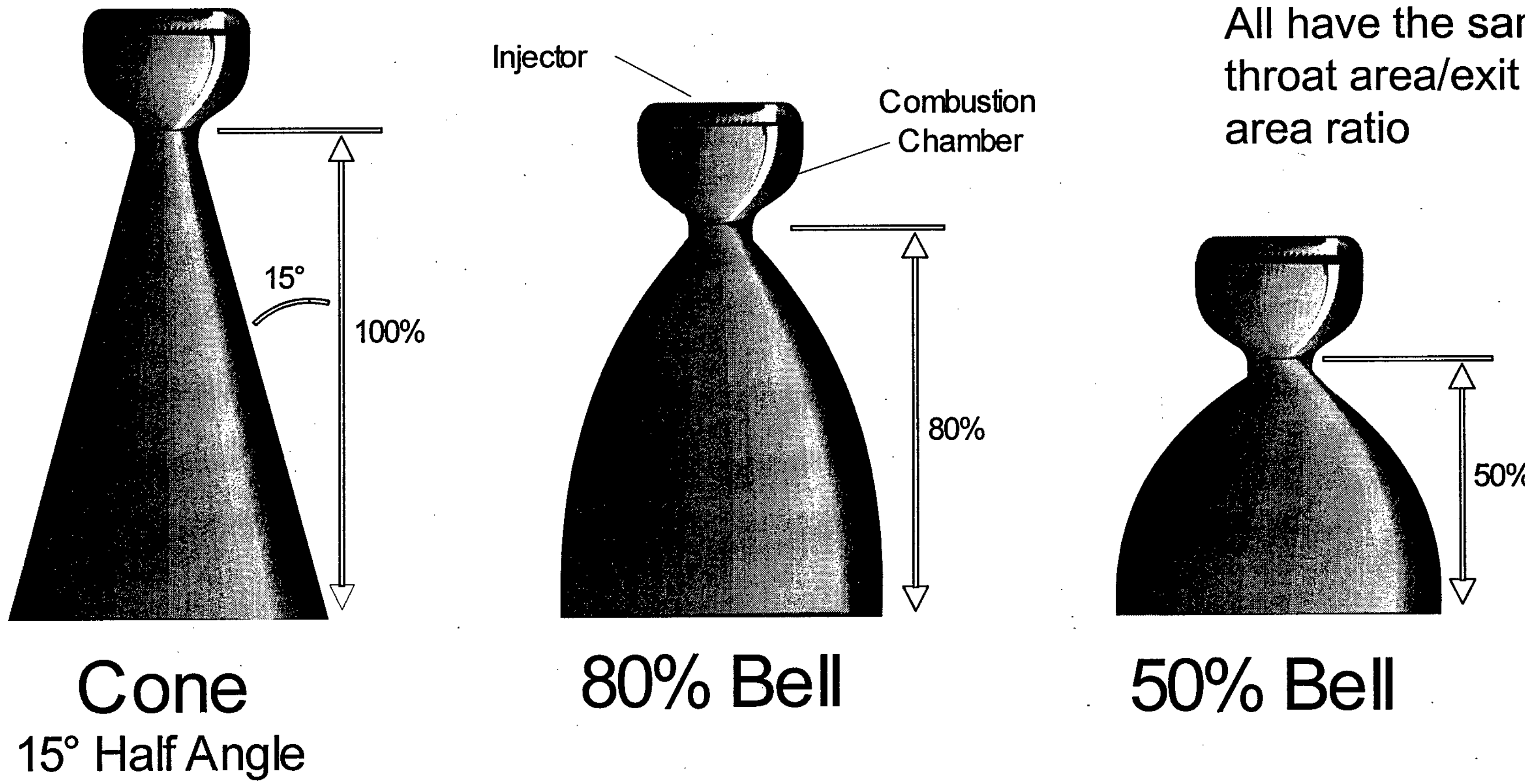
	Representative Material Property	Normal Limit	Increased Limit
Turbopump			
Pump Eff.	Heat Distortion Temp & internal friction	10% drop in Eff. 259 deg F	0% drop in Eff. Property Requires Research
Impeller Tip Speed	Modulus-Elasticity/Rigidity	1900 ft/sec	Not Challenged, no change required
Cavitation	Fluid Vapor Pressure	Function of RPM, GPM, g, & NPSH	Not Changed
Turbine Eff.	Blade Melting Temp	6% nominal eff loss	10% incr in eff.
Bearing DN	Design	20x10^6	Not Challenged, no change required
Turbine AN2	Modulus-Elasticity/Rigidity	8" RPM^2	Not Challenged, no change required

Material Limits Impacting Performance
Injector

- Material finish and orifice inlet design promote high pressure drop = lowered reliability due to increased pressure demand from pump
- Variability in material machining tolerances induce mixture ratio nonuniformity= lowered reliability and lowered thrust, this is a primary factor of combustion efficiency and stability.



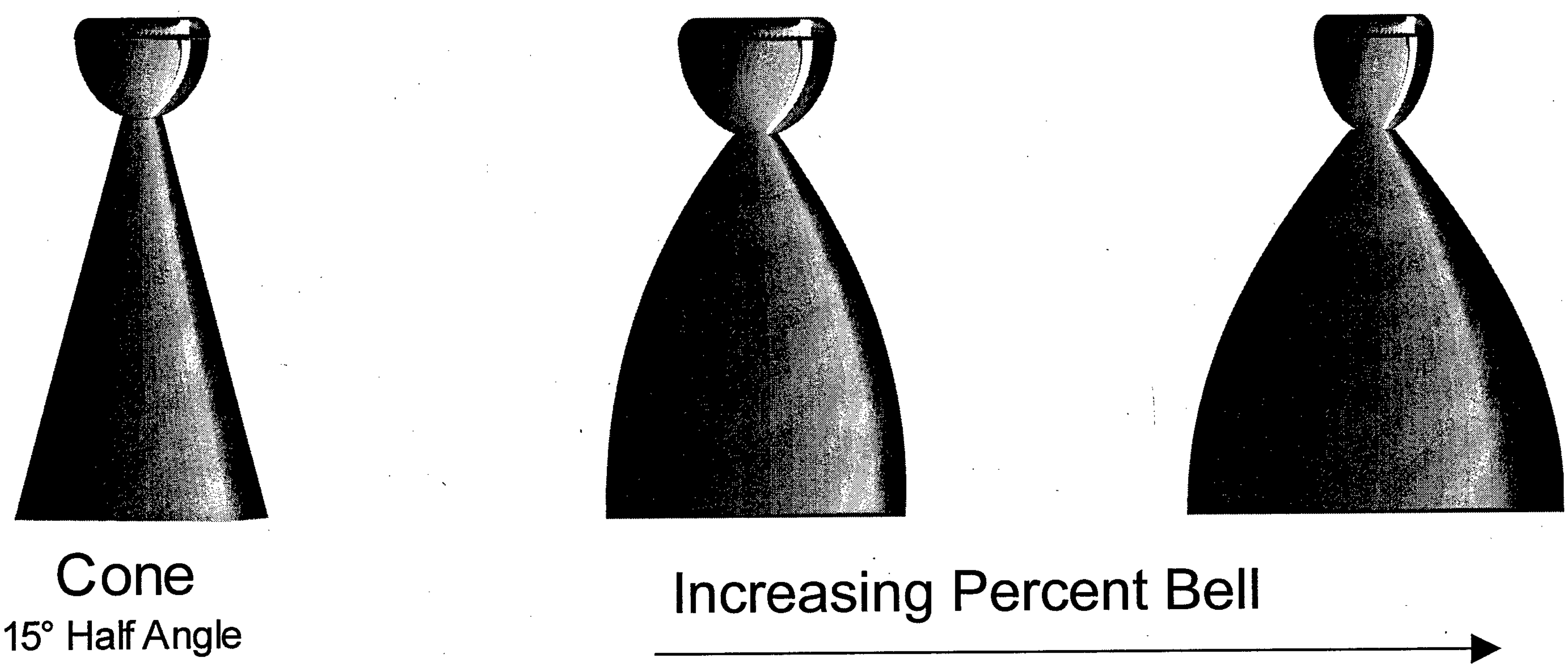
Nozzle Definition



All have the same throat area/exit area ratio

Percentage is based on nozzle length compared to the length for a 15° nozzle to get to the same exit area

Variation of Length Constrained Nozzles

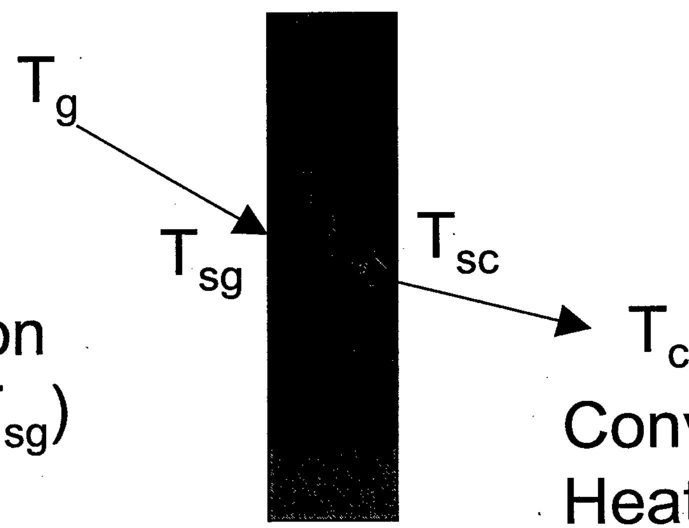


Nozzle shapes resulting from fixed length and varying area ratios

Material Limits Impacting Performance
Combustion Chamber

- Heat Load to the coolant:

Conductive
Heat Load: Q_k
$kA(T_{sg} - T_{sc})$



Combustion Gas
Heat Load: Q_{c+r}

Radiation and Convection
$h_rA(T_g - T_{sg}) + h_cA(T_g - T_{sg})$

Convective
Heat Load: Q_c
$h_cA(T_{sc} - T_c)$